CIRCUIT SIMULATION OF SATURN WITH A REFLEX TRIODE LOAD*

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Abstract

A new circuit model for the Sandia Saturn generator [1] was constructed to aid analysis of measurements from recent experiments with reflex triode loads [2]. This configuration is easier to model than others because there are no convolutes in the vacuum region. Also, the low impedance of the reflex triode makes the amount of vacuum flow current insignificant, which also simplifies analysis. Saturn has 36 identical pulse generator modules that each drive a water transmission line output. These transmission line outputs are bussed together in water before driving the vacuum insulator stack. Measured voltage waveforms from all 36 of the water transmission lines (TL) are used to drive the simulation. The 94-ns two-way electrical length between the location of the TL voltage probe and the end of the TL makes the measured TL voltages a high fidelity input for the simulation. The load currents from the circuit model are compared to measured currents for short circuit and real load shots. A physics-based circuit model for the reflex triode was used to aid in analysis of the reflex triode behavior.

I. INTRODUCTION

Saturn is a large pulsed-power generator at Sandia National Laboratories [1,4]. Saturn comprises 36 identical pulsed-power sources arranged in a circle and precisely timed together. The 36 Marx capacitor banks span the outer circumference and the vacuum load section is in the center of the machine. Between the Marx and the load, in a section filled with water, are 36 intermediate storage capacitors, triggered gas switches, pulse-forming lines, and output transmission lines. In the “fast-pulse” (~50 ns) mode, Saturn can deliver 10 MA to a 1 MeV electron-beam diode. Saturn has also been used in a “slow-pulse” (~200 ns) mode, to drive ~7 MA through Z-pinch loads.

Recent reflex triode load experiments on Saturn had several aspects that simplified circuit analysis, compared to previous experiments. In the fast-pulse mode, the entire output pulse is contained within the 2-way transit time of the constant impedance transmission line (TL), which includes a voltage monitor in each of the 36 modules. The TL voltage monitor therefore gives complete information about the output of each of the 36 modules, because the fixed transmission-line impedance gives the current. Also, with this new triode load, only 4 of the 6 stacked ring insulators are used and there are no convolutes. Convolutes in vacuum are known to give losses that can be difficult to model.

This geometry also allowed us to field vacuum voltage probes in both magnetically-insulated transmission-line (MITL) feeds (as well as extra current monitors) [2] that helped diagnose the experiment and construct the circuit model. Vacuum electron flow in MITLs can also be difficult to model, but the low impedance of the triode (and sometimes short-circuit) load reduces the amount of electron flow current to where the vacuum region can be modeled as a simple inductance.

II. CIRCUIT MODEL DETAILS

The 50-ns output pulse of Saturn in the fast pulse mode is contained within the 2-way transit time in the triplate TL section between voltage monitor and 2nd transformer, as shown in Fig. 1. This makes the TL voltage monitor an excellent place to begin the circuit model. A similar approach was also used in previous work at Sandia [5]. In this fast-pulse mode, the 36 TL voltages are sufficient to drive the circuit model. The circuit model results are valid for about 100-ns from the start of the pulse, which is more than adequate as the x-ray output of the triode load ends within 100-ns from the start of the load current.

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14. ABSTRACT
A new circuit model for the Sandia Saturn generator [1] was constructed to aid analysis of measurements from recent experiments with reflex triode loads [2]. This configuration is easier to model than others because there are no convolutes in the vacuum region. Also, the low impedance of the reflex triode makes the amount of vacuum flow current insignificant, which also simplifies analysis. Saturn has 36 identical pulse generator modules that each drive a water transmission line output. These transmission line outputs are bussed together in water before driving the vacuum insulator stack. Measured voltage waveforms from all 36 of the water transmission lines (TL) are used to drive the simulation. The 94-ns two-way electrical length between the location of the TL voltage probe and the end of the TL makes the measured TL voltages a high fidelity input for the simulation. The load currents from the circuit model are compared to measured currents for short circuit and real load shots. A physics-based circuit model for the reflex triode was used to aid in analysis of the reflex triode behavior.

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The configuration of Saturn past the triplate TL has varied considerably on different reflex-triode experiments. The configuration between TL and the reflex triode load described here is much simpler than other Saturn reflex-triode experiments.

A. Configuration of Saturn with a Reflex Triode Load

A diagram of the triplate TL section is shown in Fig. 1, where a vertical, thin high-voltage plate (shown in green in Fig.1) is sandwiched between two ground plates (one shown in blue in Fig.1), to form a constant impedance water transmission line. The constant impedance TL section is fed by a plate that narrows in height, forming an impedance transformer which increases the forward-going voltage while reducing the current. At the end of the constant impedance section, the center conductor splits and narrows to form a second impedance transformer that then feeds two rods. These rods are sandwiched between ground plates, forming constant impedance transmission lines. The high-voltage rods and vertical ground plates all connect in water to horizontal "water bottle" annular conductors. The connection between rods and bottles is called the "water convolute" and effectively adds all the rod transmission lines connected to a bottle layer in parallel. The water bottles form flat disks with water separating them, creating approximately constant impedance transmission line feeds to the vacuum insulators.

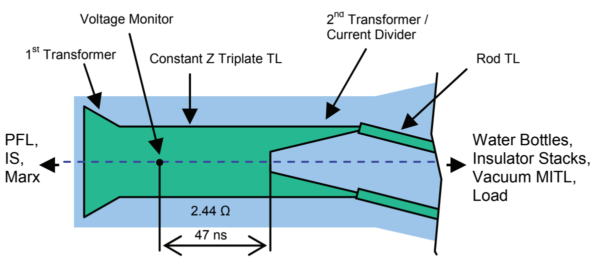


Figure 1. Diagram of the water transmission-line (TL) section of a Saturn module showing a 47-ns one-way transit-time section of constant impedance following a voltage monitor.

The usual arrangement for these experiments is to have all the rods connected to the lower two powered levels of bottles as shown in Fig. 2. The power into the bottles is then split into four levels, called A, B, C, and D, also shown in Fig. 2. Each level of bottles is modeled as a constant impedance transmission line.

The bottles end in a water-vacuum insulator. In this configuration, levels B and C drive 2-Ω MITL transmission lines connected to either side of the triode load. The B level drives the bottom half of the triode and the C level drives the upper half with equal vacuum inductances of 27.5 nH in the example shown. Levels A and D both have short circuit loads. To prevent these short circuits draining power from levels B and C and to maintain the effective polarity inversion, large vacuum inductances of 210 nH for level D and 87 nH for level A are used as "ballast" inductances.

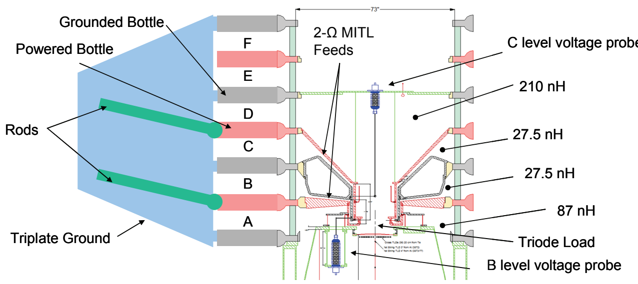


Figure 2. Diagram of the rod-bottle interface and vacuum load configuration with vacuum inductances for the A, B, C, and D levels indicated.

The circuit model described here treats the vacuum section of all for levels as simple inductors, ignoring electron flow in the MITL gaps and transit time effects. In the level B and C MITLs, the currents are very large, ~1 MA, and the voltage very low, ~250 kV. Calculating the MITL electron flow current using the Mendel formula [6], yields only ~10 kA of electron flow, which is negligible compared to the total current. Also, the transit time in the vacuum MITLs is only ~2 ns, which is small compared to the ~60-ns driving pulse width.

B. Simplified Circuit Model

Initially, the circuit model comprised 36 identical water line sections that were bussed together at the input to the water bottles. Each instance was driven by a measured TL waveform. Later, it was found a single instance of the water line section with impedances divided by 36 and driven by the average of all 36 TL waveforms gives identical results with a much simpler circuit. The simplified circuit for Saturn from the TL voltage monitors to the reflex triode load is shown in Fig. 3. The four levels of water bottles are each treated as 1.07 Ω transmission lines with a 1-way transit time of 23 ns. The bottles are split in the middle to allow comparison with voltage monitors at these locations, if desired.

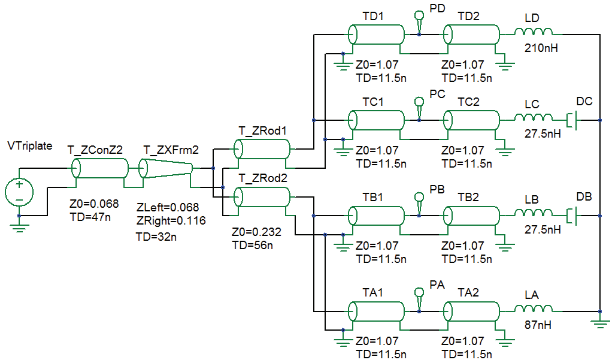


Figure 3. Simplified Saturn circuit diagram driven by average of all TL voltages on the left and inductors for the vacuum sections on the right.

This simple Saturn circuit was simulated with the NRL circuit code CASTLE, a hybrid TL and MNA (modified nodal analysis) code. A special element was added to CASTLE to accurately simulate the 2nd transformer section (T_ZXFrm2 in Fig. 3). DC and DB in Fig. 3 represent the reflex triode as two separate electron-beam diode loads at the end of levels C and B, respectively.

The measured and simulated load currents for Saturn shot 3840 with a short circuit load are shown in Fig. 4. 16 of the 36 modules were powered for this shot. The remaining 20 TLs were still connected to the water bottles. These TLs are called "get lost" lines and act to reduce power to the load. The circuit simulations match the measurements reasonably well during the 2-way TL transit time when the simulation input is valid (up to about the second peak in current at t = 400 ns).

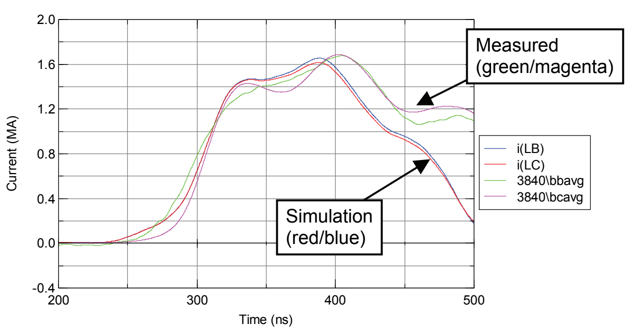


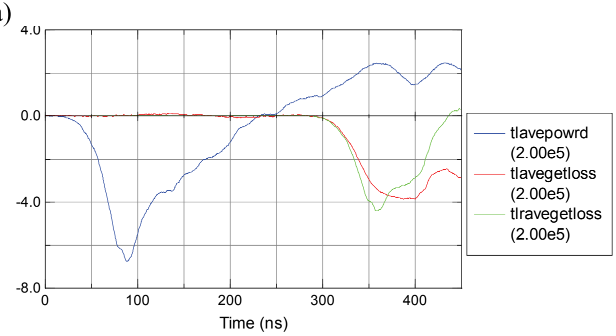
Figure 4. Measured and simulated level B and C load currents for Saturn short circuit shot 3840 with 16 of 36 lines powered.

C. Azimuthal Current Flow at Water Bottles

Although the simplified circuit model of Fig. 3 gave excellent matches to load currents, there was a significant difference in the waveforms reflected back into the TL line. This reflected signal is clearly seen on the unpowered, "get lost", TL line voltages, although it is only a clean signal for ~50 ns due to the short length of constant impedance TL line upstream of the TL voltage monitor (see Fig. 1). A comparison of the average of all measured "get lost" TL line voltages with the calculated "get lost" TL voltage from the circuit model is shown in Fig. 5a, along with the average of all powered TL line voltages. There is significant azimuthal variation in measured water bottle voltages. It was hypothesized that azimuthal current flow at the entrance to the water bottles could account for the observed difference in measured and simulated reflected voltages in the unpowered TL lines and the observed azimuthal assymetry.

A much more complicated circuit model was constructed to gauge the effects of azimuthal current flow at the entrance to the water bottles. The single-TL circuit of Fig. 3 was replaced with 36 TLs in parallel, each driven by the corresponding measured TL signal. The right, downstream sides of the 36 water bottles were all bussed together and connected to the same load inductances. New, azimuthal transmission-line elements were added to connect the input ends of the water bottles between adjacent lines. These elements allowed for azimuthal current flow at the inputs to the water bottles in a circuit model. It was found that a values of 30 Ω and 5 ns for the 36 azimuthal transmission-line elements made the average of the "get lost" reflected wave voltages much closer to the measurement, as shown in Fig. 5b. The water bottle voltages calculated this way also showed much of the same azimuthal asymmetry observed in the measured signals.

a)



b)

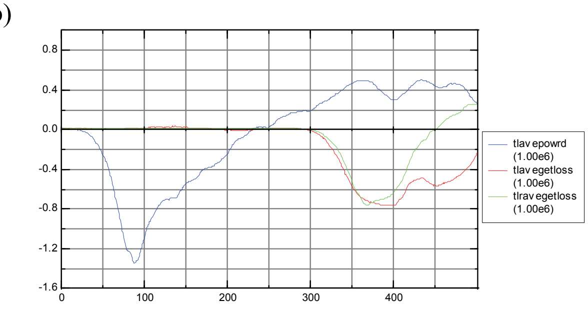


Figure 5. Measured average of all powered TL lines (blue) and the average of all unpowered TL lines (red) for a Saturn shot along with the calculated unpowered TL line voltage (green) for (a) the simple model, and (b) for a more complex model with azimuthal current elements added.

This change had very little difference on the load currents, however, as shown in Fig. 6. Only late in time, well after the x-ray output would end, does the difference become noticeable. For this reason, the simple model shown in Fig. 3 is believed to be more than adequate in spite of azimuthal current flow in the water bottles and asymmetric water bottle voltages.

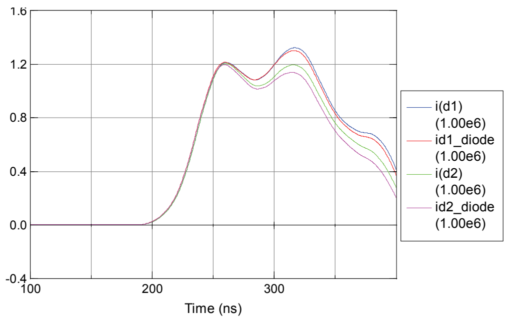


Figure 6. Calculated load currents with simple model (red and magenta) and those with the more complex model allowing azimuthal current (blue and green).

III. CIRCUIT MODELLING RESULTS

The Saturn circuit model has been very useful for understanding of several aspects of the reflex triode experiments on Saturn. The circuit model evaluated the need for a large ballast inductance in vacuum. The circuit model also helped understand how the triode behaves when coupled to a diode load. Finally, the circuit model can predict the load current and voltage for different diode loads with different numbers of powered modules.

It was initially thought that large, ~200 nH inductances were required for upper and lower vacuum ballasts on levels A and D. The circuit model determined the effects of a smaller ballast inductance. The concern was that a small inductive short-circuit load on level A would drain the power from level B. It was discovered via the circuit model, however, that the transit time of the water bottles isolates levels A and B for most of the pulse due to their 46-ns 2-way transit time. It was calculated that reducing the A level ballast inductance to 87 nH would have very little effect on the load current in level B during the time of interest.

A physics-based diode model was incorporated into the circuit model to gain further understanding of its operation. The reflex triode was represented by two pinched-beam diode models [7], labeled DB and DC in Fig. 3. In this model, the two sides of the triode are treated as independent diodes, but it should be noted that in reality there is some coupling between the two halves of the triode. The diode model includes the effects of a finite turn-on time for anode and cathode plasmas and the effect of gap closure due to the motion of these plasmas.

One of the first triode shots analyzed with this diode model, shot 3876, gave insight into diode operation and also identified some experimental issues. Using very long turn-on times for both anode and cathode, 70 and 50 ns, respectively, a good match to measured current nad voltage for the lower diode was obtained, as shown in Figs. 6 and 7. The best match was found by increasing the initial AK gap to 4.1 mm from the experimental setting of 3.6 mm. The current and voltage in the upper diode, however, could not be fit with any selection of diode parameters. This simulation work revealed a very long turn-on time for the triode, probably due to the relatively large area and low voltage. Also, some uncertainty in the actual AK gap was found, leading to more careful AK gap measurements in later shots. The discrepancy between calculated and measured voltage and current in the upper diode is believed to indicate either some power flow loss in the MITL leading to the upper diode or measurement errors on this shot.

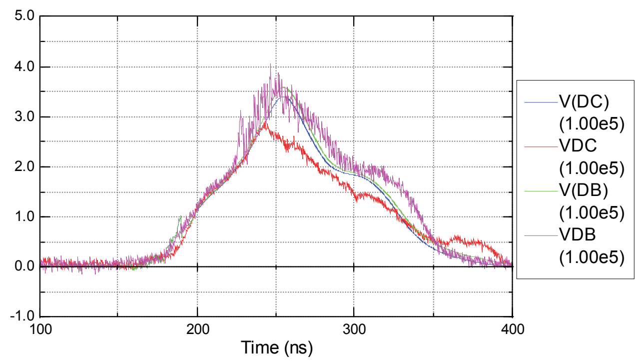


Figure 6. Measured (VDC, VDB) and calculated (V(DB), V(DC)) diode voltages for upper and lower halves, respectively, of the triode for shot 3876.

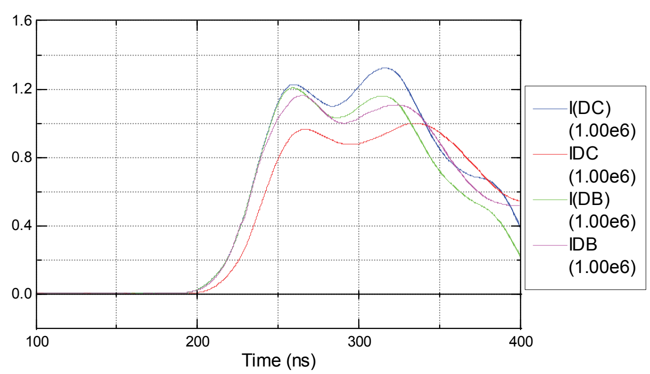


Figure 7. Measured (IDC, IDB) and calculated (I(DC), I(DB)) diode currents for upper and lower halves, respectively, of the triode for shot 3876.

Outputs of the diode model include the specified time-varying AK gap, space-charge limited current, and critical current in addition to the voltage and total current. These additional outputs show how the diode behaves during the pulse. These outputs, for the bottom diode on shot 3876, are shown in Fig. 8. The AK gap starts at 4.1 mm and drops throughout the pulse. The diode current is initially space-charge limited and then transitions to the critical current limited just prior to peak voltage.

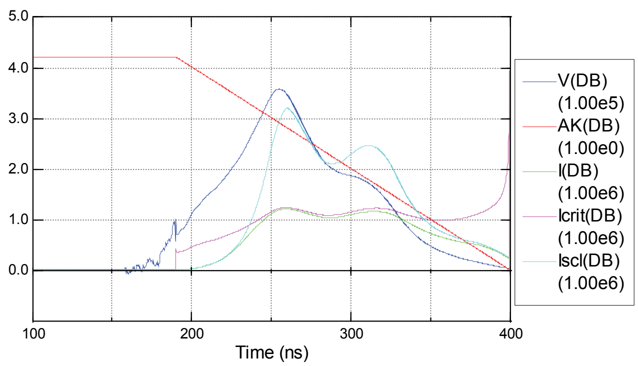


Figure 8. Plot of time-varying outputs of the diode model for a simulation of the lower diode of shot 3876 with diode voltage in blue, AK gap (mm) in red, total current in green, critical current limit in magenta and space-charge current limit in cyan.

Another use of this circuit model is to predict the load current and voltage for a given AK gap with a variable number of powered and "get lost" lines. The power to the load on Saturn can be increased by reducing the number of "get lost" lines and increasing the number of powered modules. The triode AK gap is adjusted to give the desired load voltage. This variable number of powered modules is easily simulated by simply scaling the driving TL waveform. The driving waveform for the circuit model is just the average of all measured TL waveforms from some a shot, VTriplate in Fig. 3. If N is the number of powered modules on that shot and M is the number of powered modules one wants to simulate, the driving waveform, VTriplate, is multiplied by M/N.

IV. ACKNOWLEGEMENTS

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V. SUMMARY

A new, simple circuit model has been created for the fast pulse mode of Saturn. The model is driven by measured TL waveforms. The configuration of Saturn during ongoing reflex-triode experiments allows for easy benchmarking of the model, without complexities such as post-hole convolutes. Excellent agreement between measured and calculated load currents is found. The model has been successfully used to evaluate the effects of ballast inductance, identify problems with measurements and/or power flow in vacuum, look at the details of triode operation, and predict the load voltage and current with various machine and triode configurations.

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